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EXECUTIVE SUMMARY

MINI-BRU/BIPS 1300 WATT$_e$ DYNAMIC POWER CONVERSION SYSTEM DEVELOPMENT

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
Phoenix, Arizona

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
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16. Abstract

This report contains a summary of the development status of the Brayton Isotope Power System (BIPS). A 1200 watt$_e$ ground development unit was built and tested in a 10^{-6} torr vacuum environment.

Performance mapping and 1000 hours of "proof of concept" system testing were completed.

Specific components, primarily turbocompressor alternator and recuperator, developed by the NASA from a 15 year technology base, performed according to predictions, thus achieving the design goal of 25 percent net power conversion efficiency.

The system was fabricated from superalloy (Hastelloy X and Waspaloy) thus placing it entirely within current state-of-the-art technology. The system could be flyable in the early 1980's pending flight qualification.

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FOREWORD

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NAS3-18517	Mini-Brayton Rotating Unit (Mini-BRU)
NAS3-15347	Mini-Brayton Recuperator (MBR)
NAS3-18029	Mini-Brayton Recuperator (MBR)
NAS3-18541	Heat Source Assembly (HSA)

United States Department of Energy

EY-76-C-03-1123

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SUMMARY

A closed Brayton system, producing 1200 watts of electrical power, was designed, fabricated and tested under joint sponsorship of the NASA Lewis Research Center and the Department of Energy as the initial step toward space utilization of high efficiency dynamic power conversion equipment.

The hot components were fabricated from superalloy (Hastelloy-X and Waspaloy) thus placing the system entirely within current state of the art technology. The system would be flyable in the early 1980's pending flight qualification.

Specific components, primarily turbocompressor/alternator and recuperator, developed by the NASA from a 15-year technology base, performed according to predictions, thus achieving the design goal of 25 percent net power conversion efficiency.

Performance mapping and 1000 hours "proof of concept" system testing were completed in a vacuum chamber providing a 10^{-5} torr range simulated space environment.

INTRODUCTION

The Brayton Isotope Power System program, or BIPS, represents a joint venture by the NASA Lewis Research Center and the United States Department of Energy to put into space the first nuclear isotope powered dynamic power conversion system. A conceptual flight system is shown in Figure 1. NASA developed turbocompressor/alternator, recuperator and two multi-hundred watt isotope heat source assemblies are to be combined with a radiator, controls, ducting and insulation to comprise a 1300W$_e$ system adaptable to a variety of future space missions. A schematic of the system is shown in Figure 2, and the performance specification is shown in Table I.

For a near term flight system (early 1980's), Hastelloy-X will be utilized for the hot components: heat source heat exchanger, turbine inlet plenum and connecting ducting. The selection of Hastelloy-X, with an extensive industrial history and data base, assures a state-of-the-art system and accurate predictions of life and reliability.

This baseline superalloy system has considerable growth potential. As user experience and a broader data base are obtained with refractory materials such as Columbium C-103, the turbine inlet temperature could be increased to 1600°F with an attendant increase of several points in efficiency or a reduction in system weight. Several prototype components including a turbine plenum and heat source heat exchanger have been fabricated from C-103. The use of ceramics would allow even higher operating temperatures and an additional performance increase.

The recently completed BIPS Phase I program did not have provision for the inclusion of the superalloy heat source heat exchanger (HSHX) or a space prototypical radiator. Consequently, the initial ground test system utilized electrical resistance heaters for the heat source and a gas to liquid heat exchanger for the heat rejection. These components, together with the Mini-BRU turbocompressor and recuperator, control system, ducting, multi-foil insulation and instrumentation comprised a workhorse loop, shown in Figure 3, capable of generating 1200 watts at 1400°F turbine inlet temperature.

This workhorse loop completed 1006.9 hours testing between 6 April and 22 May 1978 with no system problems. The turbine inlet temperature was maintained near 1385°F for the first 700 hours then reduced to 1100°F during the last 300 hours to prevent electrical arcing of the electric heater terminals. Electrical load was varied from 0 to 1200 watts.

Performance evaluation revealed the system design point efficiency to be 24.5 percent as shown in the test data plot of Figure 4.

Brief descriptions of the major existing components and details of the 1000 hour test are contained in the following sections.

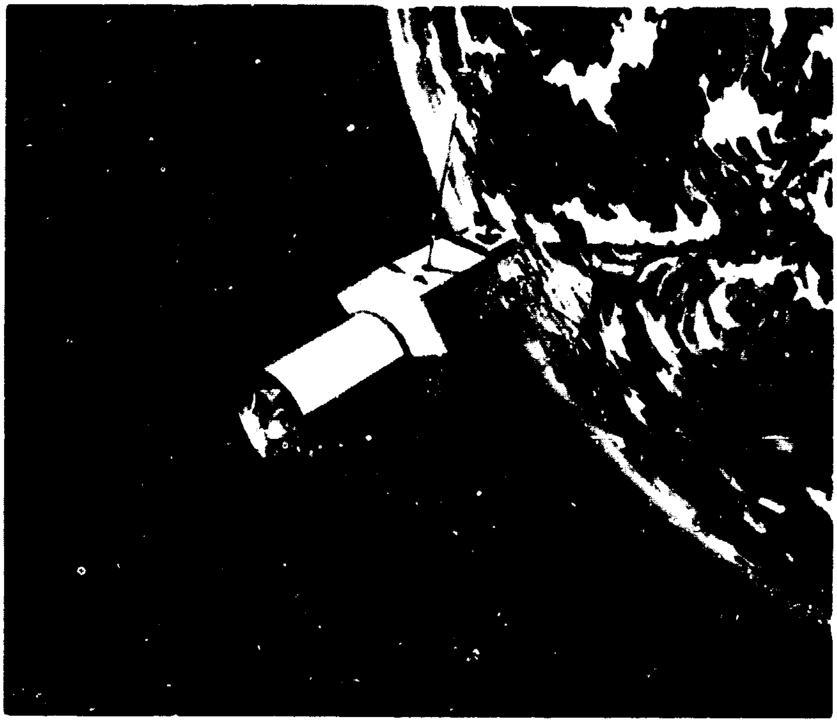

Figure 1. -1.3 kW_e Brayton Isotope Power System in Space.

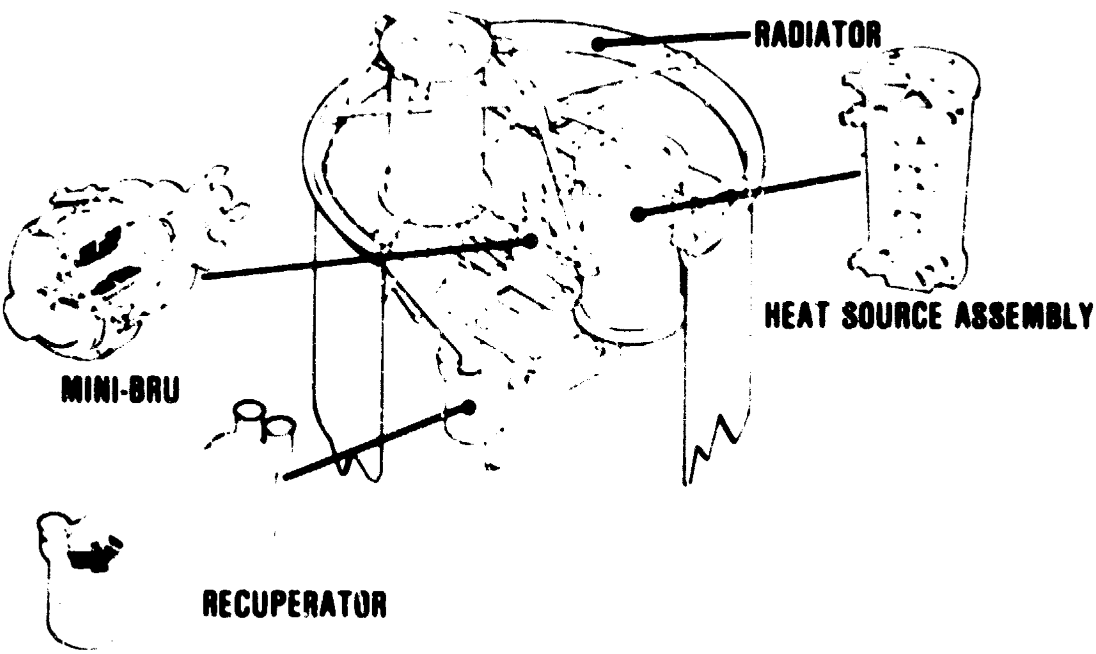

Figure 2. -Brayton Isotope Power System (BIPS).

TABLE I. - BIPS DESIGN SPECIFICATION

Design Life	7 years		
Electrical Power Output	BOM		$1300 W_e$
	BOM	5 years	$- 1235\ W_e$
		7 years	$- 1200\ W_e$
Output Voltage	120 V dc		
	Optional: 67 V ac, L-N, 3 phase 1733 Hz		
	Optional: 28 V dc		
Specific Power	6.4 W_e/kg (2.9 W_e/lb)		
Physical Characteristics			
Length	244 cm (96 in.)		
Diameter	152 cm (60 in.)		
Weight	204 kg (450 lb)		
Power Conversion Efficiency (Net)	25 percent minimum		
Design Heat Sink Temperature	216°K (-70°F)		

General Specifications

- o Mechanical, electrical, and Thermal Interface Compatible with Space Shuttle
- o Reliability = 0.95 for 5 years
- o Meteroid Protection in Accordance with NASA SP8013)
- o Shock Design Criteria for Component Mounts = 50g; Support Structure = 25g
- o Resonant Frequency >60 Hz
- o Vibration Design Criteria Compatible with Shuttle IUS Launch

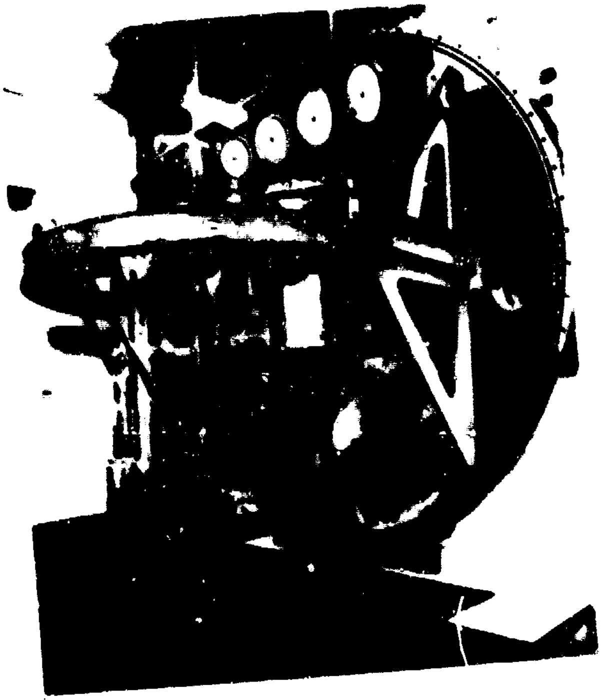

Figure 3. -BIPS Workhorse Loop.

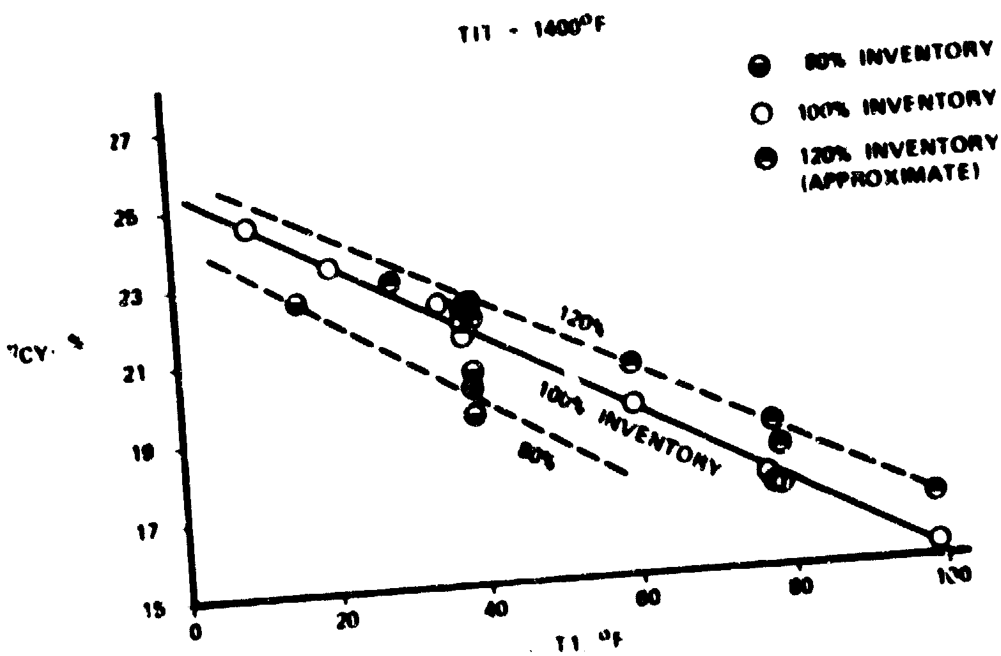

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Figure 4. -BIPS Workhorse Loop Cycle Efficiency
Versus Compressor Inlet Temperature.

MINI-BRU TURBO-ALTERNATOR-COMPRESSOR

Initial Design Philosophy

The Mini-BRU evolved from a series of NASA sponsored design studies which indicated the need for an "all-purpose" Brayton rotating unit, i.e., a unit that could be operated over a power range of 1/2 to 2 kW_e with the existing multi-hundred watt heat sources and appropriate modular recuperators.

The benefit of this philosophy is the ability to use one developed rotating unit with combinations of modularized static units to provide the electrical power needs for a variety of space missions. This philosophy is exemplified in Figure 5 which shows that only a very small efficiency and weight penalty results when compared with systems optimized for the exact power output.

The Mini-BRU design genesis lies in the big-BRU (a 6-12 kW machine) developed by the NASA and put on test in the early 1970s. This gas bearing machine has accumulated over 38,000 hours of unattended operation, without performance degradation.

Mini-BRU Description

The Mini-BRU, shown isometrically in Figure 6, incorporates a 2.84 inch diameter turbine, a 1.5 inch diameter Rice alternator rotor and a 2.12 inch diameter compressor impeller on a common shaft. Cantilevered foil journal and thrust bearings support the shaft on process fluid gas films. The bearings are Teflon coated for multi-start/stop capability and can accommodate multi-g loading over a range suitable to most missions. The alternator, bearings, and shaft are cooled by convection or conduction to the compressor throughflow either directly or via a finned heat exchanger at the alternator outside diameter. Thus, only gas cooling is used for thermal control.

No close clearance seals are utilized, the bearings themselves providing effective flow metering.

All electrical and instrumentation penetrations are made through glass-sealed connectors in the outer housing.

The component parts of the Mini-BRU are shown in Figure 7. Only eight parts comprise the total rotating group.

The turbine plenum design is such that either Superalloy or C-103 configurations may be heremetically joined with no other changes to the unit. The C-103 turbine plenum is shown in Figure 8. The turbine plenum together with the alternator housing and compressor shroud are the only three parts separated during assembly and disassembly thus minimizing the requirement for leak testing after hermetic seal welding.

Component development tests were conducted on the compressor stage, the turbine stage, the alternator and the bearings to verify the design parameters. A summary of the pertinent performance parameters is provided in Table II.

The complete analysis, design, fabrication and testing of the Mini-BRU is presented in Reference 1.

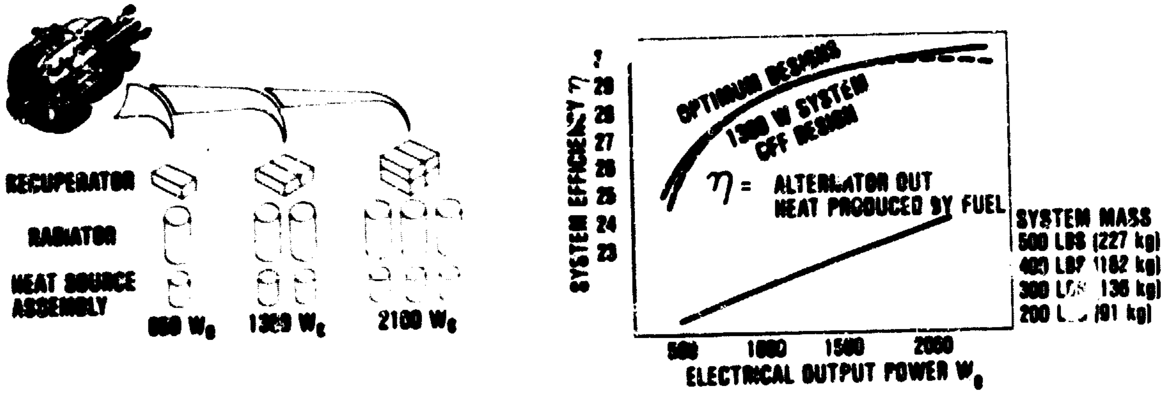

Figure 5. -Mini-BRU Flexible Modular Approach.

Figure 6. -Mini-BRU Cutaway.

Figure 7. -Mini-BRU Component Parts.

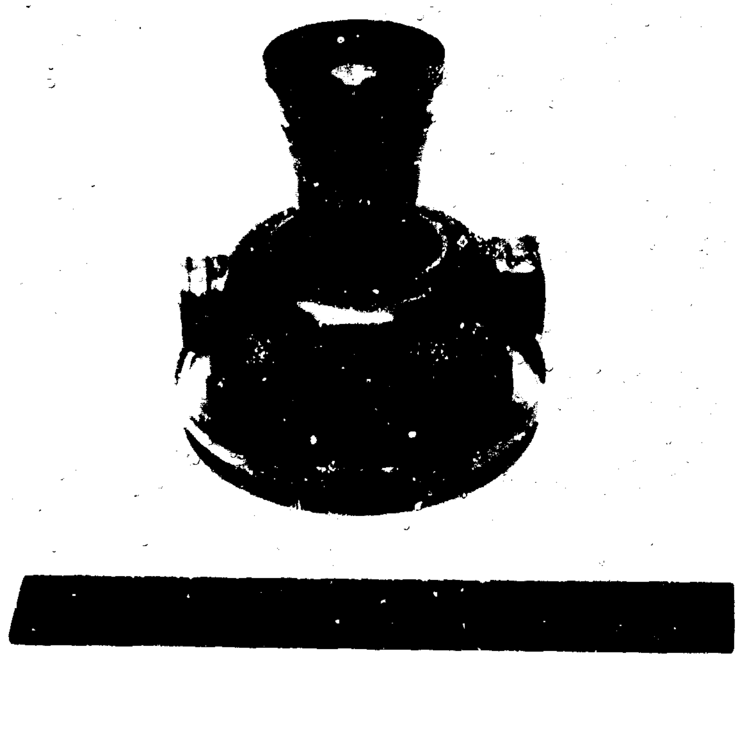

Figure 8. -Mini-BRU C-103 Turbine Plenum/Nozzle.

TABLE II. - MINI-BRU COMPONENT SPECIFICATIONS

Compressor

Type - Radial Outflow (backward curved vanes)
Diameter in. - 2.12

Pressure ratio - 1.62
Corrected flow lb/sec - 0.103
Efficiency, %-77
Life - unlimited

Turbine

Type - Radial Inflow
Diameter, in. - 2.84

Tip Speed, ft/sec - 644
Corrected flow, lb/sec - 0.0996
Inlet temp, °R - 1845-2060

Efficiency %-83.6

Life - unlimited

Alternator

Type - Rice
Diameter, in. - 1.50
Tip speed, ft/sec - 250
Power output - 500-2100 watts
Number poles - 4
Life- unlimited

Journal Bearings

Type - Cantilvered foil
Diameter, in. 1.038
Power loss, watts - 45 per bearing
Load capacity - 3G minimum
Lubricant - Xe-He
Life - 10 years

Thrust Bearings

Type - Cantilevered Foil
Diameter, in. - 1.80
Power Loss, watts - 110 per side
Load capacity - 6 G minimum
Lubricant - Xe-He

Life - 10 years

Recuperator Heat Exchanger

Type - Counterflow Plate-fin
Size in. - 22.6L x 10.9H x 5.8W
Total pressure drop LP, 1.1%
Hot side inlet temp, °R - 1569-1755
Design Average Effectiveness: 96.5%
Life - 200 start cycles or 10 years

Heat Source Heat Exchanger

Type - One Pass Helical Coil
No coils - 10
Tube diameter, in. - 1.56
Tube wall thickness, in. - 0.05
Discharge temp, °R - 1853
Life - 10 years minimum

RECUPERATOR

Concept

The BIPS recuperator was an evolution of 15 years of NASA-Lewis sponsored technological development. The design approach involved the development of a modular unit which could be combined with the all purpose Mini-BRU in appropriate configurations to meet the system performance requirements. The analysis, design and fabrication of the recuperator is presented in Reference 2.

The primary design goals included high reliability, realistically achievable performance and minimum weight. Low cycle fatigue from repeated startup and shutdown cycles was identified as the critical structural design problem. The design goal entailed 100 thermal cycles (220 cycles were analytically predicted).

Configuration

The recuperator is of welded and brazed construction and is fabricated entirely of Hastelloy-X. The internal configuration is a pure counterflow plate-fin arrangement as shown in Figure 9. Other pertinent parameters are given in Table II. Palniro (gold) alloys are used to braze the assembly into a leak tight configuration.

Thermal tests conducted with air as the working fluid indicated that the unit met or exceeded its performance goals. Both the predicted effectiveness and thermal conductance (UA) were exceeded. This was subsequently verified in the BIPS loop testing where an overall average effectiveness of 96.5 percent was attained.

A full scale prototype recuperator was subjected to 200 thermal cycles. After 100 cycles there was no external leakage and a minute amount of internal bypass flow. After 200 cycles there was still no external leakage, internal bypass flow had increased to about 0.2 percent of the total flow which would be negligible from the point of view of recuperator performance.

The recuperator configured for assembly into the BIPS WHL is shown in Figure 10.

Figure 9. -Mini-Brayton Recuperator Core Assembly.

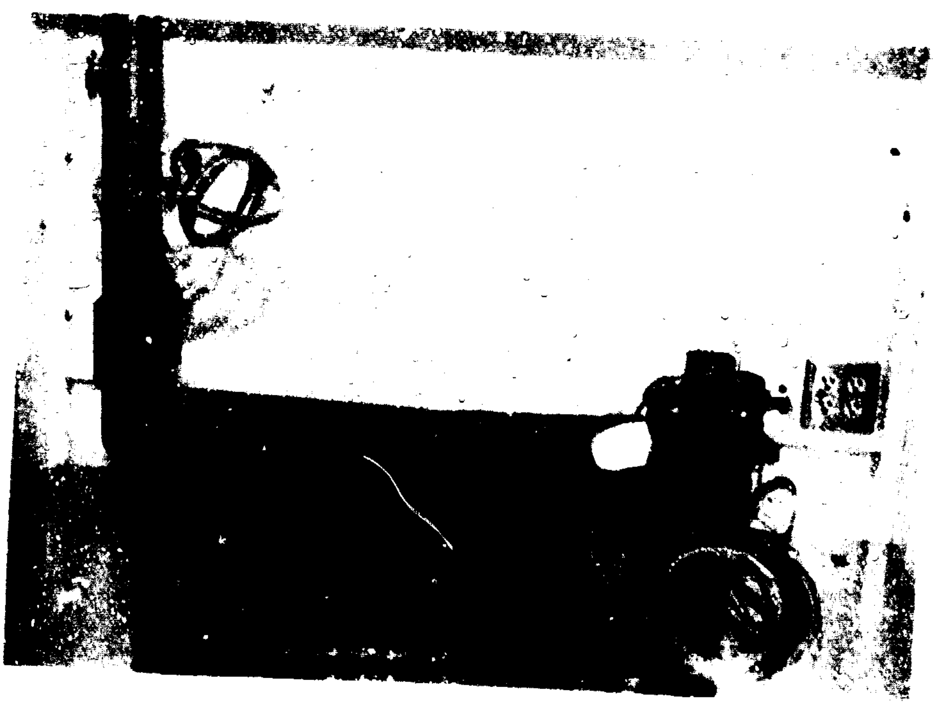

Figure 10. -Mini-Brayton Recuperator Configured for BIPS Workhorse Loop.

HEAT SOURCE ASSEMBLY

Concept

The isotope heat source for the BIPS was modeled after the highly successful Radioisotope Thermoelectric Generator (RTG) multi-hundred watt heat source assembly (HSA) utilized in the Mars-Jupiter-Saturn missions.

For adaptation to the closed cycle BIPS, a C-103 axial flow heat exchanger was designed and fabricated by the General Electric Company (Reference 3). A cutaway isometric view of the HSA is shown in Figure 11. Heat is generated by the plutonium fuel spheres, conducted through a graphite containment cylinder and radiated to the heat exchanger. The heat exchanger in turn is enclosed by some 60 layers of thin multi-foil insulation which serves a dual function. In addition to limiting heat loss to the outside, the multi-foil acts as an agent of the emergency cooling system. If the unit temperature exceeds a certain threshold, the multi-foil layers will commence melting until an equilibrium is reached; the heat will then be radiated to the surrounding environment.

Superalloy System

For the baseline superalloy system, a Hastelloy-X heat source heat exchanger was designed and fabricated (Reference 4). A simple helical coiled tube, shown in Figure 12, was employed for the cycle gas heat exchanger. The maximum metal temperature employed in the design of this heat exchanger was 1450°F which is compatible with the 7 year life requirement. Performance parameters and data relative to the design are provided in Table II. The heat exchanger coil, assembled into the HSA, (with the end dome removed) is shown in Figure 13.

Due to scheduling limitations during the Phase I program, the coiled tube HSA assembly was not installed and tested in the loop. Instead a simple electrical resistance heated configuration was employed for the workhorse loop tests.

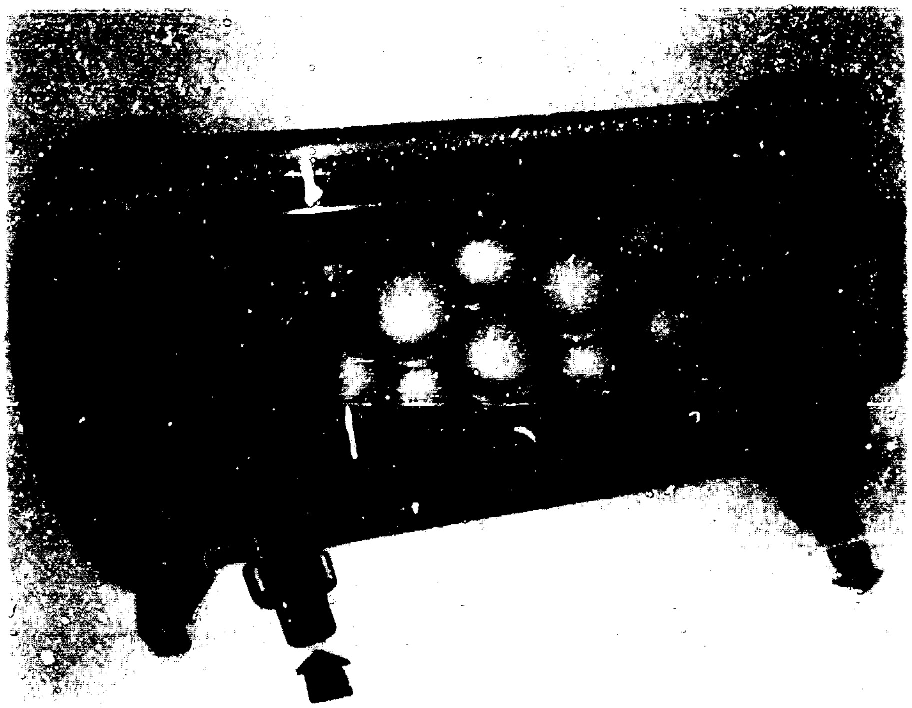

Figure 11. BIPS Heat Source Assembly (HSA).

Figure 12. BIPS Hastelloy-X Heat Source Heat Exchanger.

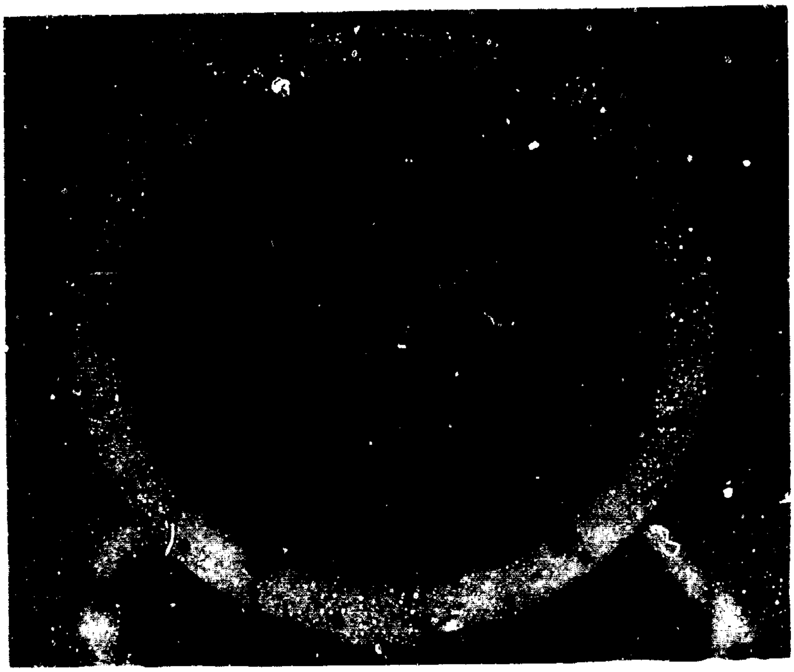

Figure 13. -Heat Source Assembly (End Dome Removed) Showing Heat Source Heat Exchanger, Multi-Foil Insulation and Multi-Hundred Watt (Electric) Heat Source.

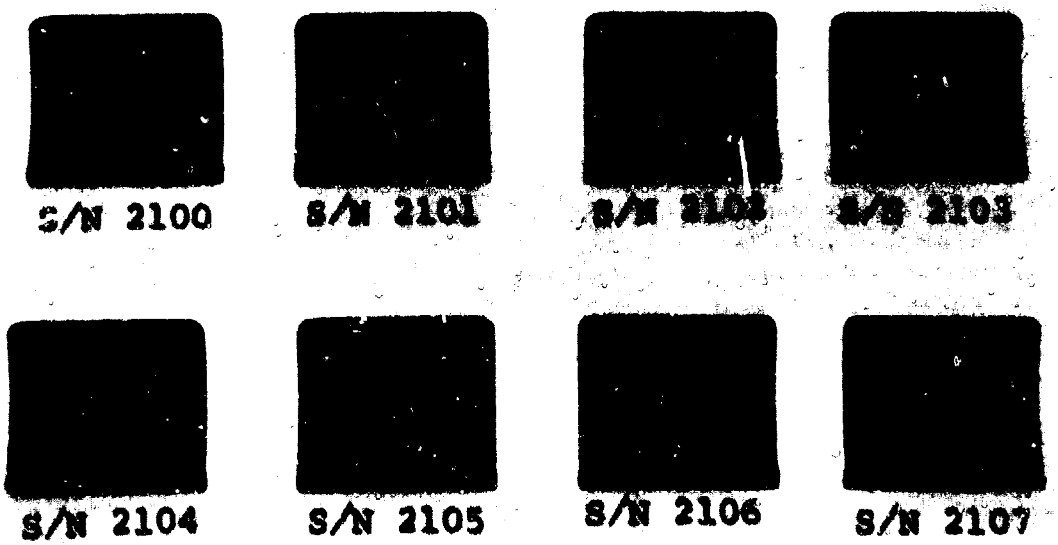

Figure 14. -Mini-BRU Compressor End Journal Bearing Foils After 1000 Hour Test.

WORKHORSE LOOP SYSTEM TESTS

Two key contractual test objectives were the demonstration of 25 percent power conversion efficiency and 1000 hours of endurance testing.

Tests were conducted in a specially developed vacuum chamber with the capability of 10^{-6} torr. This was essential to simulate the space environment and assure the proper performance of the multi-foil insulation utilized on the hot components.

The first hot test of the workhorse loop and its components resulted in a failure of the compressor end foil journal bearing. Inspection following the second hot test revealed some deterioration in the same bearing. Detailed analyses and bearing tests were conducted to define the problem (Reference 5). The most probable cause of failure was determined to be a thermal decrease in bearing clearance and poor adhesion of the Teflon coating. Corrective measures were taken and no further problems were encountered. Accelerated life testing of the Teflon in a controlled environment indicates that the bearing anti-friction coating has an operational life of seven or more years.

Performance tests were conducted from November, 1977 through February 1978. A system efficiency of 24.5 percent was attained at the 1385°F turbine inlet temperature.

The endurance test objective was completed over the period from 6 April 1978 through 22 May 1978 when 1006.9 hours of testing were completed. No system problems were encountered during the test period. System operation was interrupted three times during the test period by support equipment malfunction but the closed loop remained intact and was routinely restarted each time.

At the conclusion of the test the rotating unit was disassembled and inspected. Every element was in excellent condition. Photographs of the compressor and turbine end foil journal bearing sets are shown in Figures 14 and 15. A photograph of the two foil thrust plates is shown in Figure 16. No unusual or abnormal wear or degradation was evident anywhere on the bearings. Slight burnishing (normal) had occurred in the load carrying zone from the numerous start-ups. A film of very fine carbon powder was observed on the turbine end foils. This carbon had migrated through the cooling gas circuit from a test instrumentation continuity/ground probe at the compressor end of the rotating group.

The turbine inlet temperature was maintained at 1385°F for the first 700 hours of testing. A problem with electrical arcing on the terminals of the heater elements forced a reduction in temperature to 1100°F for the last 300 hours. The turbine temperature was increased to 1400°F at the conclusion of the test to verify that no unit deterioration had occurred. The maximum bearing temperature observed during the test was 253°F at the compressor journal bearing carrier.

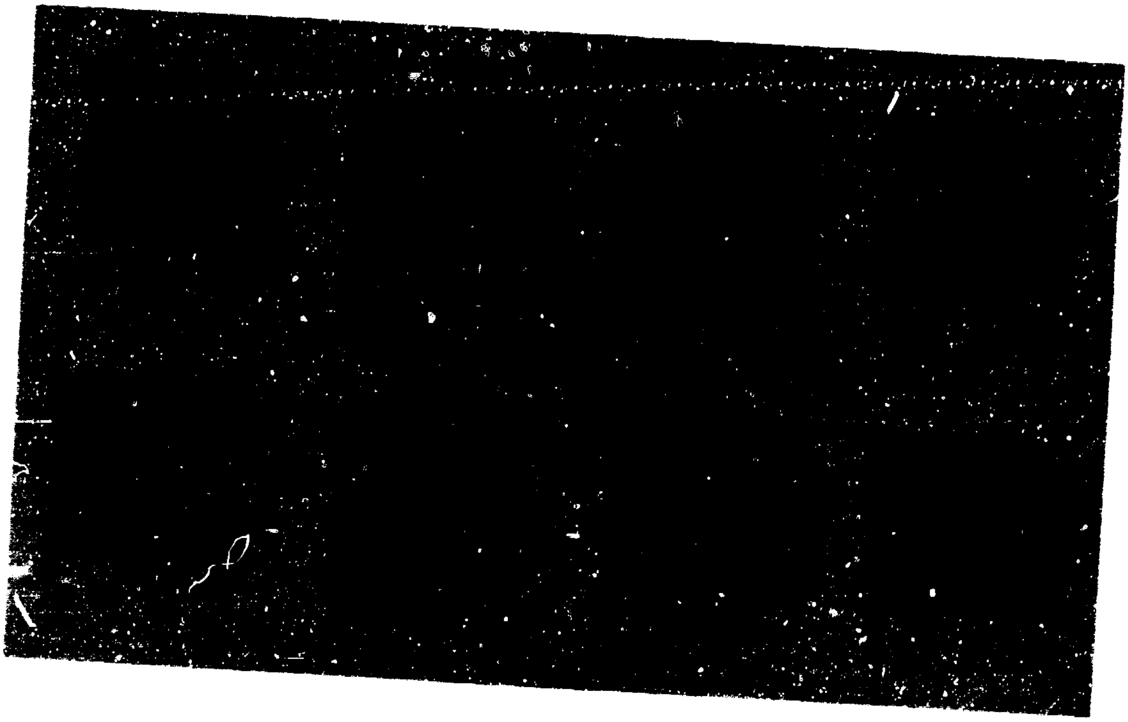

Figure 15. -Mini-BRU Turbine End Journal Bearing Foils After 1000 Hour Test.

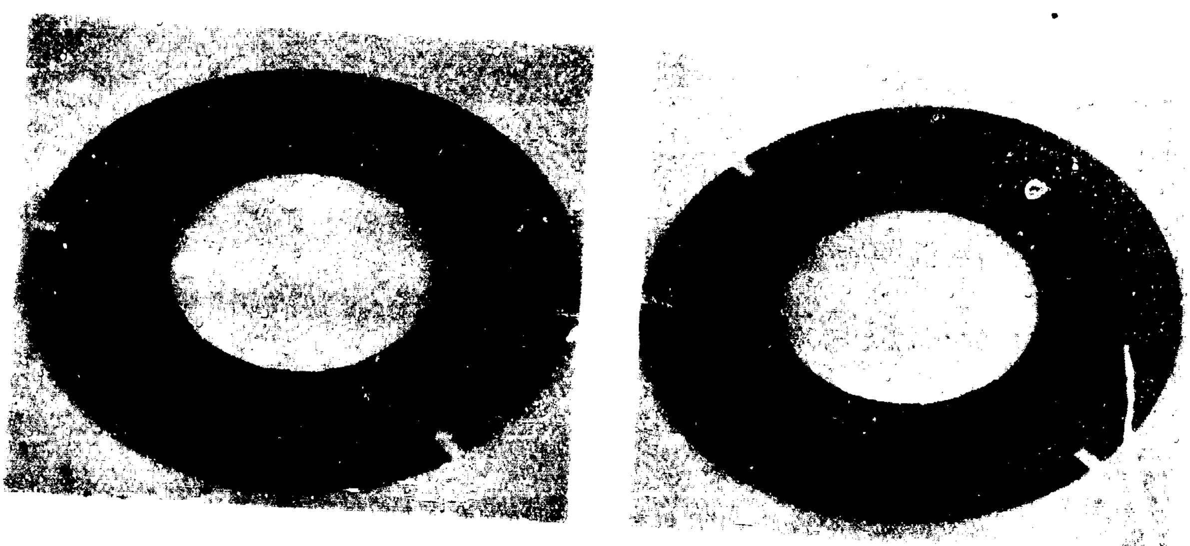

Figure 16. -Mini-BRU Foil Thrust Bearing Pads After 1000 Hour Test.

CLOSURE

The design and test efforts conducted over the past several years have shown the BIPS to be a viable system for further development into a flight configuration capable of sustained operation in space. It represents the only known dynamic space power system to demonstrate the required performance and endurance together with the simplicity necessary for reliable unattended operation.

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